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Articulating Fold Mirror for the Wide-l~icld/1'l:irlcttlry Camera 11

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ABSTRACT

A very compact tip/tilt, mirror has been developed for the Wide-1~icld/1'larrctary Camera 11, a science instrument that is to be installed in the Hubble Space Telescope to restore the Hubble's imaging performance. The Articulating Fold Mirror (AFM) is a space qualified, ultraviolet compatible device that incorporates many advanced features including a highly lightweighted mirror and electrostrictive solid state actuators that provide precise and repeatable open loop performance. The design, fabrication, and testing of the AFM arc described.

1. INTRODUCTION

The Wide-1~ield/1'lanctary Camera (WF/PC) is the principal science instrument aboard the Hubble Space Telescope. At the time the Hubble Telescope was launched in 1990, a flight spare camera, WF/PC-2 (essentially a copy of WF/PC), was being built at JPL. The significance of WF/PC-2 changed dramatically when it was discovered that the Hubble Telescope primary mirror suffered from several waves of spherical aberration, seriously impairing the optical performance of the telescope and its instruments.[1] It was quickly realized that by making a minor change to the WF/PC-2 optical design, it would theoretically be possible to correct the Hubble wavefront error and restore the imaging performance to nearly the original specifications. Moreover, since the WF/PC-2 was already well along in fabrication, an opportunity existed for a relatively quick and low cost fix to the Hubble's imaging problem. A servicing mission was subsequently scheduled for 1993 to replace WF/PC with WF/PC-2 using astronauts working from the Space Shuttle. Apart from a desire to correct the imaging performance at the earliest possible date, the schedule for the first servicing mission was also under pressure due to certain engineering problems discovered with the Hubble that were thought to place the health of the observatory at risk. Fig. 1 shows a cutaway view of WF/PC-2.

The method for correcting the Hubble wavefront error has been detailed elsewhere;[2] it is useful to visualize the approach as that of cancelling one error (in the Hubble) with an opposite "error" placed on one of the WF/PC-2 mirrors. 'l'his is straightforward in principle, but is made difficult in practice by the large magnitude of the error that must be corrected. It was determined by calculation that the alignment precision required to effect the wavefront correction was an order of magnitude more stringent than the original tolerances for WF/PC-2, and represented a degree of alignment stability well beyond what the WF/PC-2 had been designed to deliver. in addition, circumstantial evidence suggested that the on-orbit alignment of WF/PC was drifting over time; similar drifts in WF/PC-2 could render the correction ineffective. A means of guaranteeing on-orbit alignment was needed.

The Articulating Fold Mirror (see Fig. 2) assures that the WF/PC-2 optical trains can be aligned within the required tolerance to restore the Hubble imaging performance. The remainder of this paper details the requirements for the AFM subsystem and describes the design, fabrication and flight qualification of the active mirrors; the associated drive electronics arc not discussed. It is noteworthy that the decision to develop the AFMs was taker] with less than two years remaining before the required delivery of the completed WF/PC-2 instrument. In order not to impact the delivery schedule, the flight, qualified AFM mirrors were needed for integration into the optical bench less than 10 months from the time the decision was made to develop them. The schedule and fiscal constraints, together with the tight packaging requirements that will be described later, compelled the team to adopt a "skunk works" approach to the AFM development.

2. OPTICAL ALIGNMENT

The WF/PC-2 instrument consists of three f/] 2.9 and one f/28.3 optical trains that must be in alignment simultaneously. A typical optical train is depicted in Fig. 3. The optical design places the exit pupil of the Hubble

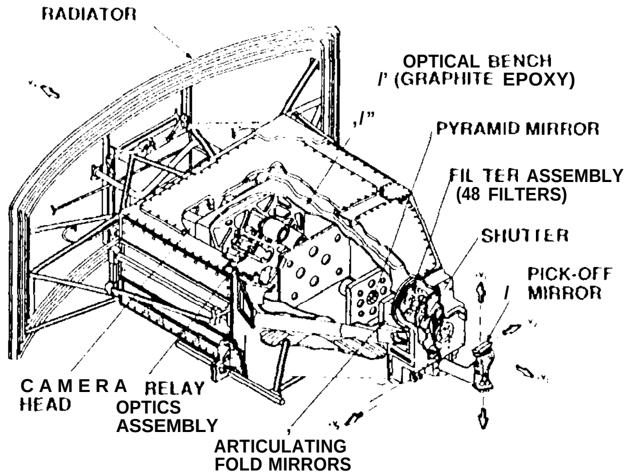

Fig. 1. Cutaway view of WF/PC-2 instrument.

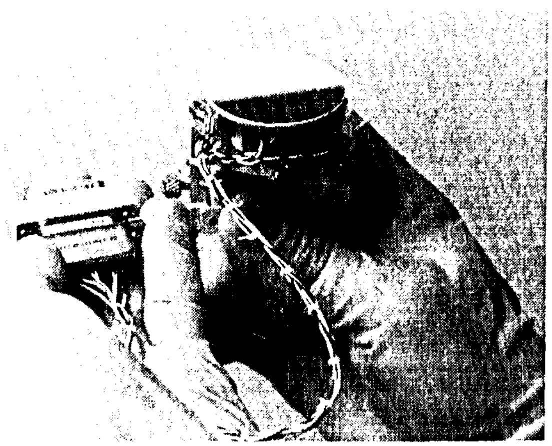

Fig. 2. Articulating Fold Mirror.

Telescope onto the secondary mirror of the relay optics. Each secondary mirror is polished to a shape that exactly matches the error in the Hubble primary mirror. If the exit pupil is centered on the secondary mirror, then the image formed at the focal plane is well corrected. If the pupil is offset to one side (pupil shear) then the image formed at the focal plane will exhibit coma. In order to restore the Hubble imaging performance to its original specifications, the on-orbit pupil shear resulting from all sources cannot exceed 0.4 percent of the pupil diameter (approximately 50 microns at the secondary mirror). The most straightforward means of adjusting the position of the pupil on-orbit is by controlling the tip and tilt of the fold mirror in each optical train. This is the function of the Articulating Fold Mirror. Pupil shear can be corrected in one of the four optical trains by means of the actuated pickoff mirror. Three AFMs arc used to correct the residual pupil shear in the remaining three optical trains.

3. REQUIREMENTS

3.1. Functional requirements

A system level error budget was developed to assure on-orbit alignment. The AFM functional requirements that flow from this error budget arc summarized in Table 1. The tip/tilt range requirement for the mirror is a measure of the worst case uncertainty associated with the pupil alignment likely to be achieved on-orbit. A fold mirror tilt of 206 arc sec (1 mrad) corresponds to 4.8 percent pupil shear. The Project established a goal of aligning the instrument on the ground such that no on-orbit adjustment would be required. Consistent with this goal, the AFM is required to remain in its ground aligned "home" position within ±10 arc sec through launch and transition to on-orbit environmental conditions, and to return to the "home" position automatically should there be a failure in the actuation electronics of the AFM subsystem.

Table 1. Functional requirements

Tip/Tilt Range	$\geq \pm 206$ arc sec ($\pm$ 1 mrad)
Short Term (2000 second) Stability	<4:1.8 arc sec
Long Term Stability	$\leq \pm 13.6$ arc sec
Ground-to-Orbit Stability	$\leq \pm 10$ arc sec
Repeatability	$\approx \pm 1\%$ (± 2 arc sec)
Tilt Step Size	$\approx$ 1 arc sec

Stability of the tilt angle is broken into short term stability (2000" seconds of time) and long term stability. Short term stability is driven try the requirement that the image on the focal plane remain stable during an exposure to within one tenth of a pixel; long term stability is driven by the requirement that the pupil in each of the optical trains remain in alignment to within 0.4 percent pupil shear. The Hubble Telescope is operated as a rmrl-real time

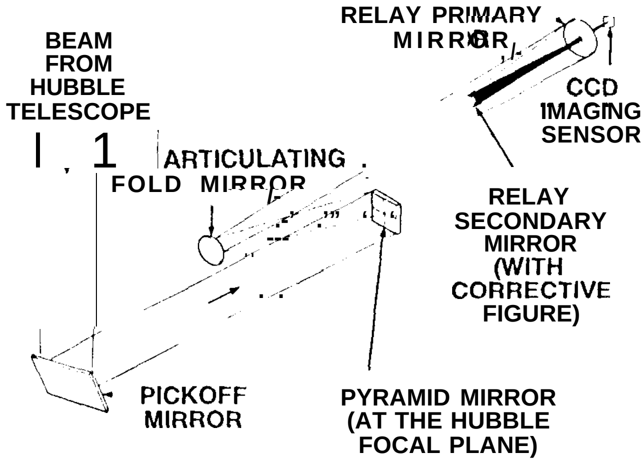

Fig. 3. Typical optical train of WF/PC-2.

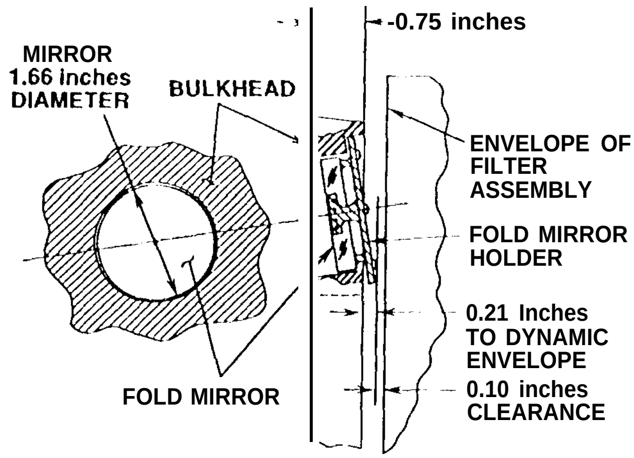

Fig. 4, Fixed fold mirror in optical bench showing packaging constraints.

system; in order to reduce the time required to align WF/PC-2, the AFM is required to operate predictably and repeatabl y within ±1 percent full range.

3.2 Optical requirements

Two AFMs were needed for the f/12.9 and one for the f/28.3 optical trains. Table 2 lists the optical requirements for the AFM reflecting surfaces.

Table 2. Optical requirements

Scratch/Dig	20-5 per MIL-O-13830
Surface (f/12.9)	flat
Surface (f/28.3)	convex; radius=. 231.2 inch ± 1 inch
Surface Deviation (at 6328Å)	$\leq \lambda/100$ RMS
Surface Roughness	≤ 20Å RMS
Reflectance at 1216A	$\geq 78\%$
Reflectance at 2537Å	$\geq 86\%$

3.3 Temperature and contamination requirements

A unique feature of the Hubble Telescope is its ability to see the universe at ultraviolet wavelengths because it is outside the earth's atmosphere. Ultraviolet performance is a high priority for WF/PC-2, and consequently a rigorous contamination control plan has been adopted. All materials used in the AFM are required to be "clean" with respect to the generation of particles and condensible volatile gases. Typically, WF/PC-2 components are baked out in vacuum to drive off all condensible volatiles. This is an expensive process that can take many days. Increasing the bakeout temperature shortens the bakeout duration; therefore, it is desireable that the AFM be compatible with as high a temperature as possible. The final design is compatible with 125°C bakeouts. To prevent contamination from condensing on the cooled focal plane detectors in flight, it is desirable that the WF/PC-2 operate at as cold a temperature as feasible. The AFMs were required to operate at as close to 0°C as possible.

4. PACKAGING CONSTRAINTS

The most significant engineering challenge involved packaging the AFM such that it could replace an existing *fixed* fold mirror in the optical bench. The decision to develop the AFM was made at a time when most of the WF/PC-2 hardware was in the final stages of fabrication, including the optics. The fixed fold mirror was designed to

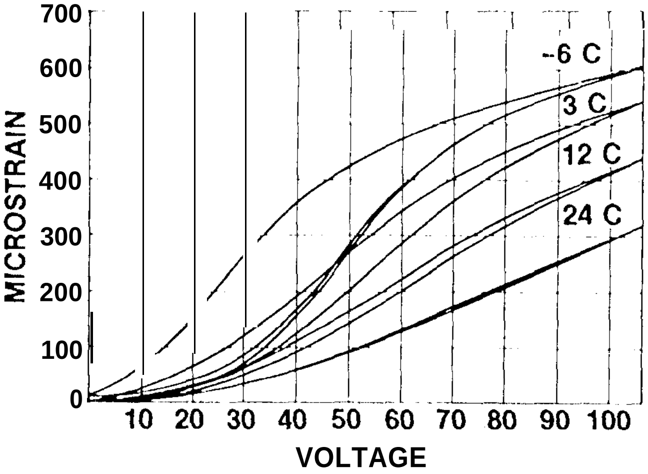

Fig. 5. Electrostrictive actuator strain vs. voltage at various temperatures.

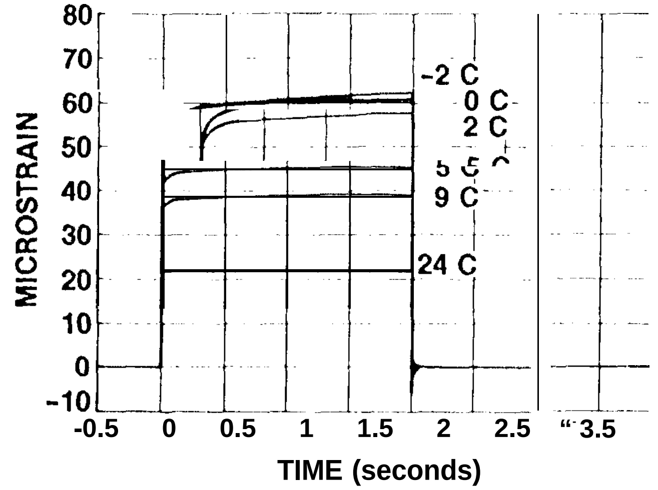

Fig. 6. Actuator response to step voltage change showing stable zero strain state.

fit entirely within a clearance hole in an Invar bulkhead of the existing optical bench. The front surface of the mirror could not be moved forward without affecting the optical design of the instrument, and the back of the mirror holder could not be moved rearward due to the proximity of an existing filter wheel assembly. The packaging constraints can be appreciated from Fig. 4, which depicts a typical fixed fold mirror in the optical bench bulkhead.

The narrow clearance between the fold mirror bulkhead and the filter wheel assembly meant that the cabling to the AFM needed to be minimized. Since the actuator drive electronics was also being added to the existing instrument, its size, power and weight also needed to he minimized. This argued against having position sensors in the AFM for feedback control, with their associated conditioning electronics and cabling.

5. FEASIBILITY STUDY

Given the severe packaging constraints, it was not immediately obvious that a device could be designed that would meet the functional requirements. Prior to making a decision to proceed with the AFM, the WF/PC-2 Project commissioned a two month feasibility study. The objectives of the study were to produce a conceptual design together with COSL and schedule estimates for the development of flight qualified AFMs.

5.1 The Prime mover

The packaging constraints made a conventional motor and gear-train approach (such as that used for the actuated pickoff mirror) impractical. Three alternative solid state prime movers were evaluated: magnetrostrictive alloy, piezoelectric ceramic, and electrostrictive ceramic. Magnetostrictors and piezoelectrics were rejected because of their hysteresis and tendency to drift, which would have required the addition of feedback sensors in the AFM to meet the repeatability and stability requirements. Electrostrictive ceramic composed of lead magnesium niobate (PMN) appeared to offer the required precision, but the behavior of PMN at the required operational temperature was unknown. Electrostrictive ceramic multilayer actuators were originally developed by Litton/Itek Optical Systems for deformable mirror applications and consequently Itek was invited to become a partner in the AFM development.

5.2 Characterization of electrostrictive ceramic actuators

An intensive experimental investigation was undertaken to characterize the behavior of the Itek electrostrictive ceramic actuators over the temperature range of interest. The actuators are nearly ideal electrical capacitors. Static actuation involves charging them with a dc voltage; once energized, the actuator draws nanoamp level current. At several temperatures, three cycles of 1 Hz sine wave voltage were applied and the corresponding strain response was measured. The results are plotted in Fig. 5. The quadratic strain response characteristic of electrostrictive ceramic is readily apparent.[3] Three temperature dependant phenomena are evident from Fig. 5. First, the magnitude of the strain increases with decreasing temperature, being most sensitive to temperature near 5 deg C. Second, hysteresis increases steadily as the temperature is reduced. And third, for the lowest temperature curve, two different upward

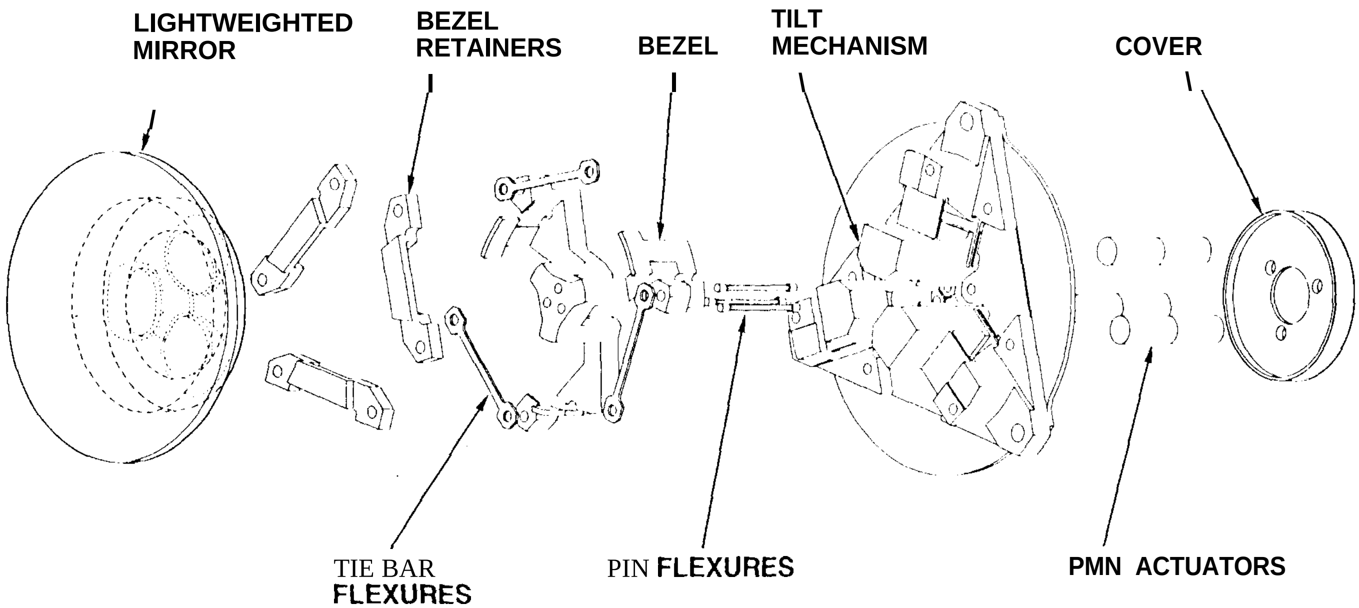

Fig. 7, Exploded view of Articulating Fold Mirror.

manifolds can bc seen, which indicates that the strain had not returned to zero from the first cycle of voltage before the next cycle was applied. Fig. 6 sheds rnorc light on this third point. These plots show the strain response to step changes in applied voltage. At room temperature, the strain response is nearly instantaneous; at lower temperatures, the final strain state is approached more slowly. A very important feature of the electrostrictive ceramic is that, even at reduced temperatures, the strain appears to return to zero when the applied voltage is returned to zero, although it may take a few seconds. This feature is referred to as a stable zero strain state, which permits the AFM to be operated in a repeatable manner even in the presence of hysteresis. Changes in mirror position arc accomplished by first “resetting” the strain to zero and then increasing the voltage monotonically to the desired value.

5.3 Conceptual design

Four conceptual designs were developed during the feasibility study. The complexity of the various designs was in proportion to the degree to which the ceramic actuators were protected against tensile stress. The simplest design was preferred from the standpoint that the actuators could be integrated into the mechanism using the same methods developed by ltck for deformable mirrors. The negat ive aspect, of this design is that the actuators become primary structural components (as they arc in deformable mirrors) and thus arc subjected to tensile stress when the mirror is actuated and during launch vibration. Two engineering model mirrors based on this simpler concept were fabricated during the course of five weeks.~ These mirrors performed as predicted, validating the concept as well as the modelling and fabrication techniques employed. The rapid development of the engineering model mirrors was influential in the final decision to proceed with the flight AFMs, since unprecedented speed would be required to meet the Project schedule.

6. FLIGHT AFM DESIGN

The decision was made to base the flight design AFM on the engineering model mirror developed in the feasibility study since this mirror had met the tip/tilt requirement of ±1 mrad, and would permit Itek to integrate the actuators in a familiar manner. The design was not yet suitable for flight, as no attention had been paid to stresses associated with the launch vibration environment, and the position of the reflecting surface was much too far forward, i.e., not compact enough. ltck experience suggested an allowable tensile stress for the electrostrictive actuators of 1000 psi. The initial design goal for the AFM was to withstand 200 g acceleration while keeping actuator stress below 500 psi (the goal was not quite met), and to achieve 1 rnrad mirror tilt, with no more than 300 microstrain in the actuators.

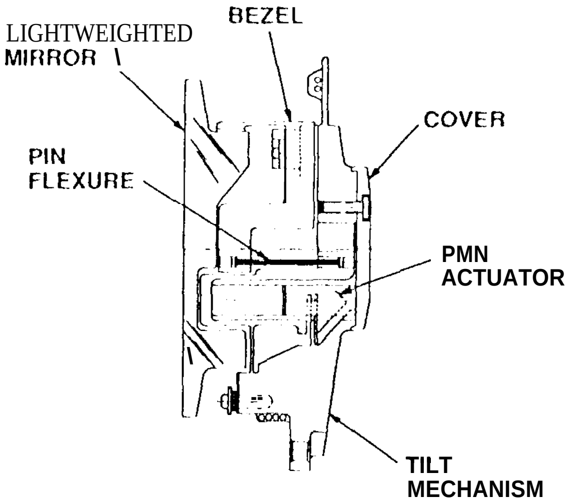

Fig. 8. Section view of Articulating Fold Mirror.

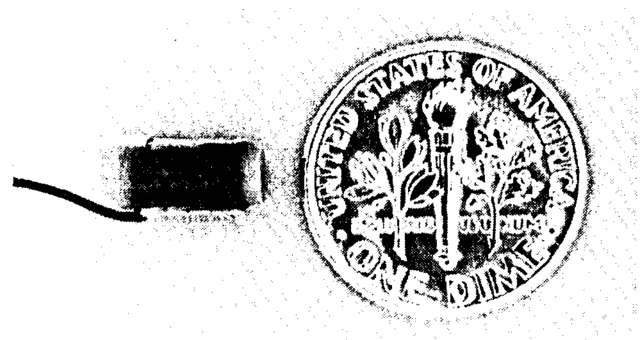

Fig. 9. Itek SELECT electrostrictive actuator segment (0.150 inch diameter).

G.] Configuration

Fig. 7 shows an exploded view and Fig. 8 a section view of the flight AFM design. The fused silica mirror is supported at three locations around its perimeter by three flexure tines of the Invar bezel. The bezel is bonded to the mirror with RTV 566 silicone rubber nominally .011 inches thick. The bezel is attached to the Invar tilt, mechanism via three pin flexures and three tic-bar flexures. The pin flexures arc bonded at the tilt mechanism side to three lugs. Each lug protrudes from a canister that houses a two segment electrostrictive actuator. The canisters arc supported by two-blade parallel motion flexures that arc integral to the tilt mechanism. The two segment actuators arc bonded at one end to the inside of the canister and at the other end to the cover. All actuator bonds are made using EpoTek 353ND epoxy, and all flexure bonds are made using EA9394 epoxy with BR127 primer.

6.2 Kinematics

The tilting of the mirror is accomplished as follows: An electrostrictive actuator is energized electrically, causing the length of the actuator to increase. The actuator reacts against the cover, pushing the canister forward (guided by the parallel motion flexures). As the canister moves forward, its lug pushes the pin flexure forward, which in turn pushes the bezel forward at its point of attachment. The remaining two pin flexures resist the forward push, resulting in an overturning moment on the bezel. The bezel tilts accordingly (the pin flexures bend in the process) carrying the mirror with it.

Because the pin flexure is offset from the centerline of the canister, resistance to forward motion at the bezel creates a bending moment back on the canister and actuator that is effectively resisted by the parallel motion flexures. Lateral support to the bezel is provided by the three tic-bar flexures. These arc carefully positioned in the same plane as the center-of-gravity of the rrlirror/bezel combination .s0 that lateral acceleration does not cause a bending moment due to cg off.set and a corresponding rotation of the bezel, This has the combined effect of minimizing gravity offload rotation of the mirror, minimizing stress in the pin flexures, and minimizing angular jitter in the mirror due to on-orbit microphonics.

G.3 Actuator geometry

The schedule constraints precluded the manufacture of custom actuators for the AFM. Fortunately, Itek possessed residual stock actuator segments of the 0.150 inch diameter SELECT design,[3] one of which is shown in Fig. 9. The actuator segments arc approximately 0.340 inches in length and consist of approximately 39 active layers, each .007 inches thick. Itek operational experience suggests that, the safe limit for strain irr the segment is approximately 450 microstrain. This value was derated to 300 microstrain for the AFM, which corresponds to an applied voltage of approximately 90 volts at room temperature. At 300 microstrain, cacti actuator segment provides a linear stroke of approximately 2 microns. The tilt angle achievable for a given linear stoke of the actuator is governed by how

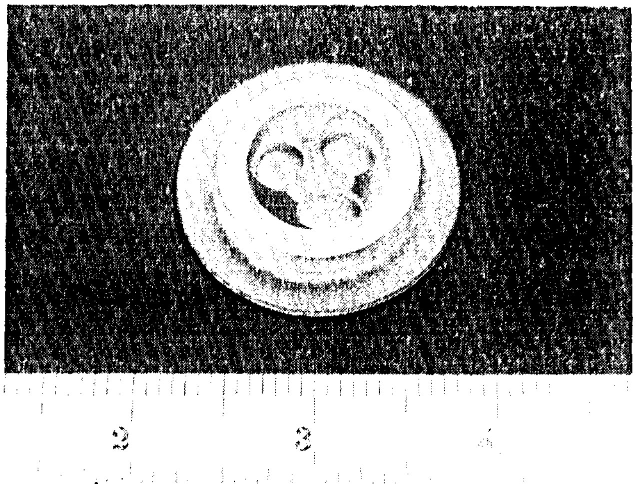

Fig. 10. Lightweighted mirror machined from fused silica.

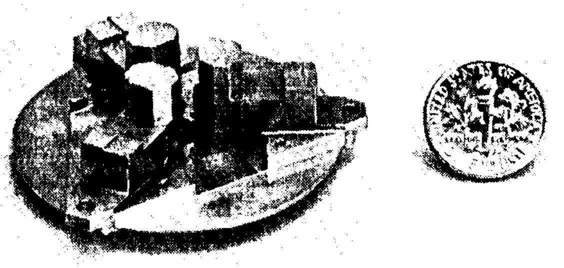

Fig. 11, Tilt mechanism machined from a monolithic block of Invar 36.

close the pin flexures arc located to the centerline of the assembly (0.06 inches in the AFM). Clearance limitations suggested that a minimum of two actuator segments (end-to-end) would be required to reach the 1 mrad tilt requirement. Each actuator therefore consists of two segments, independently addressable by the drive electronics. This also provides tip/tilt redundancy to onc hal f full range should one of the segments in each actuator become inoperable. Three actuators are arranged at 120 degree positions around the centerline of the AFM as shown in Fig. 7.

6.4 Lightweighted mirror

In order to place the reflective surface of the mirror at the desired location, the maximum allowable thickness of the AFM, measured from the front surface of the mirror to the back of the cover, is 0.880 inches. Given that the actuators themselves arc approximately 0.680 inches in length, it was decided to light weight the mirror try machining cavities in the track surface. Approximately onc half of the glass was removed in the lightweighting process. The tilt mechanism canisters extend into the clearance cavities. The lightweighting has the added advantage of reducing the total rotary inertia of the tilting portion of the AFM. The lightweighted mirror is seen from the back side in Fig. 10.

6.5 Structural analysis

A detailed finite element model was developed to analyze stresses and deflections due to articulation of the tilt mechanism, launch vibration, and thermal effects. 'The mirror was also modelled in detail to assure that the reflecting sur-face would remain in specification at the operating temperature. The lowest frequency modes of vibration arc the tip/tilt modes at approximately 400 Hz. The structural analysis and modelling arc described in greater detail elsewhere.[5]

6.6 Operational temperature range

The symmetry of the AFM design makes the mirror tilt angle inherently insensitive to coefficient of thermal expansion (CTE) effects. In addition, the design is athermalized try matching the CTE of the tilt mechanism (Invar 36), the mirror (fused silica), and the actuators (electrostrictive ceramic). Therefore, when the AFM is in an unpowered state, i.e., in the "home" position, the tilt, angle is insensitive to temperature. Temperature sensitivity of tilt angle arises almost entirely from temperature dependence in the relationship between strain and applied voltage in the actuators. From Fig. 5 it was seen that the temperature sensitivity reaches a maximum near 5°C. Two conclusions earl be drawn from this. First, the sensitivity of AFM tilt angle to temperature is proportional to the degree to which the AFM is commanded to tilt. Second, the stability of the AFM tilt angle is governed not only by the stability of the voltage applied to the actuators, but also by the stability of the temperature of the AFM and how near that temperature is to 5°C.

An inspection of on-orbit data from WF/PC together with thermal analysis suggests that the optical bench temperature stability over a 2000 second period is approximately 0.07° C. Combining this stability value with the short term tilt angle requirement of Table 1. and the measured strain sensitivity of Fig. 5 determines the lowest, temperature at which the AFM can be commanded to full range (1 mrad) and still meet the stability requirement. This temperature is computed to be 10"C, and sets the lower bound on operational temperature. Room temperature is the warmest operational environment encountered by the AFMs and therefore sets the upper bound.

7. FLIGHT AFM FABRICATION/ASSEMBLY

7.2 Mechanism fabrication

All metallic components of the AFM are fabricated from Invar 36 alloy. The tilt mechanism, bezel, and flexures were machined in large part by the wire electro.discharge machining (EDM) process. This enabled the tilt mechanism in particular to be machined as a monolithic component (see Fig. 11). The surfaces of the parallel motion flexures, pin flexures and tie-bar flexures were machined by a two-pas. EDM procedure that produced the finest surface finish possible to maximize fatigue life.

7.3 Mechanism assembly

The metallic components of the mechanism were assembled at JPL. The alignment of the bezel, tilt mechanism and pin flexures was established by mate}) drilling the six holes that the pin flexures are bonded into using a master drill fixture. O-ring seals of RTV 566 were cast, near the ends of the pin flexures to center the flexure in the hole, and to prevent adhesive from spreading beyond the bond surface (see Fig. 12). All bond surfaces were acid etched with sulfuric acid/sodium dichromate thixotropic paste, and desmutted using a thixotropic slurry of nitric acid and deionized water. EA9394 epoxy was injected into the pin flexure bond cavities of the tilt mechanism and the pin flexures positioned. After curing, the bezel was positioned and bonded to the pin flexures. Finally, the tie- bar flexures were bonded into position. After assembly, a final inspection of critical dimensions was performed and the subassembly was delivered to Itek for integration of the actuators and mirror.

7.4 Actuator and mirror installation

At Itek, the actuators were prepared by lapping and bonding two electrostrictive segments together in a v-block fixture. The 30 gage teflon insulated wire leads were bonded to the edge of the segments using H20E silver filled conductive epoxy. The actuators were then surrounded by teflon shrink tubing and baked in an oven at 120°C. The shrink tubing functions as a st rain relief to the wire leads.

When the JPL subassembl y was received at Itek, critical dimensions were reinspected. The unit was installed in tooling to support the cantilevered bezel flexure tines, and all surfaces to be bonded were grit blasted with aluminum oxide air brasive powder. The subassembly was ultrasonically cleaned in spectral grade ethyl alcohol.

The actuators were then centered and bonded to the inside of the tilt mechanism canisters; the bonds were cur-ed at 120°C. The depth of the canisters and the length of the actuators were carefully matched so as to expose a few thousandths of an inch of actuator beyond the back of the tilt mechanism. The three exposed ends of the actuators were lapped flat and co-planar with the back of the tilt mechanism using silicon carbide sand paper bonded to optically flat glass. A prescribed amount of adhesive was applied to the ends of the actuators and the cover, which was then bonded into position and cured at 120° C. Great care was taken to control and remove particles generated by the lapping process.

Thin sheets of RTV 566 were cast and cured on a surface table. Pads of this prepared material were cut to size and bonded to the surfaces of the bezel tines using fresh RTV 566. The mirror was strip coated to protect the polished surface and placed face down on a surface table covered by an acetate alignment template. The pads of RTV that had previously been bonded to the bezel were coated with fresh RTV and the subassembly was carefully lowered into position above the mirror, the RTV making contact with the edge of the mirror. Thin layers of SS4155 primer had been applied to the Invar and fused silica bonding surfaces. The assembly was allowed to cure for one week at 50 percent relative humidi ty in this configuration.

7.5 Lead dress

All sharp edges in proximity to the teflon coated wire were either covered with acrylic adhesive Kapton tape or stycast 2850] ''7', catalyst 9 adhesive as a precaution against cold flow short circuiting. The wires were carefully

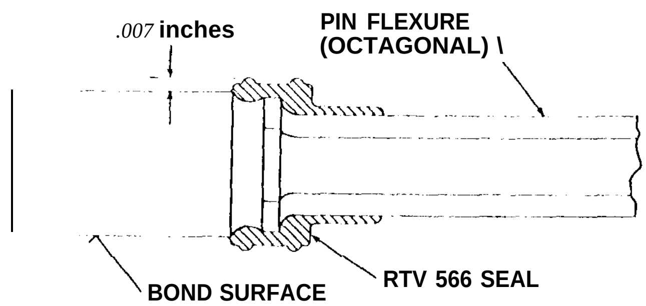

Fig. 12. Detail of RTV seal on pin flexure.

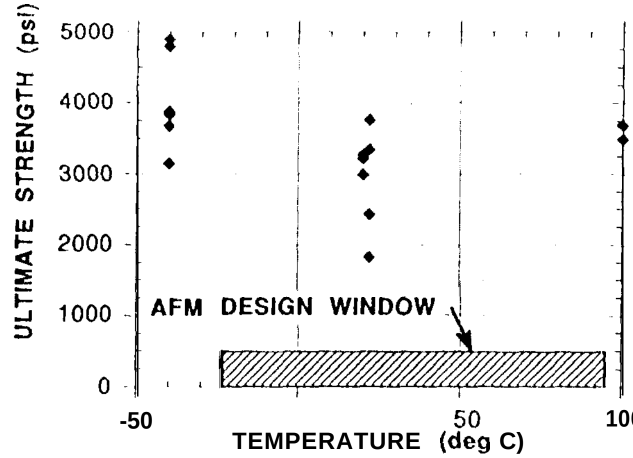

Fig. 13. Electrostrictive actuator pull test results.

routed through the mechanism and staked at several locations using stycast. Back at JPL, the wires were routed on a cabling mockup of the optical bench bulkhead, cut to length and crimped to a 15-pin connector, The connector backshell was potted with RTV **566** for strain relief.

8. ENVIRONMENTAL TESTING

8.1 Thermal vacuum testing

Each AFM was subjected to a thermal cycle test in vacuum. Typically, the AFM was mounted to an Invar plate with a fixed reference mirror attached. The alignment between the AFM and the reference mirror was monitored during the test to verify that the unpowered "home" position of the mirror was stable across temperature. The prototype AFM was cycled four times between – 15°C and + 40° C, with one hour soaks at the upper temperature and one-half hour soaks at the lower temperature. All subsequent AFMs were subjected to a single temperature cycle. The AFM was verified to remain in the "home" aligned position to better than 5 arc sec over a temperature swing of 10"C.

A flight, spar-c AFM was put through an aggressive series of operational tests at 10°C and 15°C in vacuum. These tests included calibration of tilt vs. voltage as a function of temperature, repeatability of commanded tilt angle, and the measurement of timing functions to reach steady state after a change in voltage. At the coldest operational temperature of 10°C the AFM was found to be repeatable to within ±1 %, the zero strain state was stable within 2 arc sec, and the time to reach stable tilt was less than 10 seconds.

The flight spare was also subjected to a 1000 cycle li fe test at, 10°C, where one cycle consisted of a voltage ramp to 90 volts and then back to zero. No change in operational performance as a result of the life test was detected. The mirror figure was also measured at 10" C to verify that no distortion of the reflective surface occurs at operational temperature.

8.2 Random vibration testing

A random vibration test of each AFM was performed at the assembly level. A flight spare AFM was tested to protoflight amplitude;[5] the remainder were tested to flight acceptance amplitude (– 4db from protoflight). Because of the low mass (105 gram) and fragile nature of the AFM, it was decided that the vibration test should be of the force limited type.~ This is a relatively new test methodology that automatically accounts for the flexibility of the mating hardware that the test article attaches to in flight (in this case the optical bench). A reference mirror was attached to the test fixture and the alignment of the AFM relative to the reference mirror was measured before and after the test. The AFM was verified to remain aligned within 3 arc seconds. Pre and post shake functional tilt tests were also performed to verify no change in performance. All AFMs passed the assembly level vibration tests without incident.

8.3 Proton radiation test

The electrostrictive ceramic material had not previously been space qualified, and questions remained regarding the effects of energetic protons on the performance of the actuator. A proton radiation test was conducted using one of the engineering model mirrors developed during the feasibility study. This mirror was mounted adjacent to a reference mirror with one of the three actuators energized to full voltage. Both mirrors were monitored during the radiation exposure to detect any drift in the position of the mirror that would suggest a problem with the actuator. No drift was seen at 100 krad exposure level. No change in performance was detected as a result of the test.

8.4 Actuator tensile test

Because the electrostrictive actuators are exposed to tensile stress in the AFM, additional testing was performed on similar segments bonded to Invar pull tabs. The test segments were tested to failure at various temperatures in a tensile test, machine. These results of these tests are shown in Fig. 13. These data suggest a 3σ tensile strength of 1188 psi, supporting the Itek design allowable stress of 1000 psi.

9. MIRROR COATING

9.1 Vacuum bakeout

After environmental testing, the AFM was baked out in vacuum at 95°C for approximately one week to drive off condensible volatiles in preparation for the coating of the reflective surface. After coating, the AFMs were typically baked out, for an additional week before being certified at +20°C to less than 1 nanogram/cm^2 per hour condensation rate on a surface (quartz crystal microbalance) held at - 70" C.

9.2 Mirror cleaning and coating

The requirement for high efficiency ultraviolet performance demands that the coated mirror be maintained in a very clean condition. For this reason it was decided that the coating of the mirror would be performed as the last step. In order for the coating to properly adhere to the mirror substrate, the substrate must be molecularly clean. Typically this is achieved by rinsing the mirror in a series of solvents, ending with Freon TF to provide a water break free surface. Cleaning the AFM with Freon presented a significant risk that the Freon would be absorbed into the organic adhesives, creating a later outgassing contamination problem in vacuum. With much difficulty, a cleaning fixture was designed that incorporated a latex condom and a surgical glove to seal off the mechanism from the front surface of the mirror. This fixture was successfully used to clean the AFM mirror substrates immediately prior to coating. The mirrors were coated with an Acton 1'200 coating (aluminum overcoated with magnesium fluoride) that approached near theoretical reflectance values in every case.

10. AS-BUILT PERFORMANCE

The as-built performance of the AFM is summarized in Table 3 together with the performance specifications. As can be seen, the as-built performance achieves or surpasses all functional and optical specifications.

Table 3. As-built performance summary

	specification	as -- built‡
Tip/Tilt Range at 22° C	-	± 208 arc sec
15°C	≥ ± 206 arc sec	± 254 arc sec
10°C	≥ ± 206 arc sec	± 298 arc sec
Short Term (2000 second) Stability*	≤ ± 1.8 arc sec	± 0.5 arc sec
Long Term Stability†	≤ ± 13.6 arc sec	± 7 arc sec
Repeatability	≈ ± 1% (±2 arc sec)	≈ ± 1%
Surface Deviation (at 6328Å)	≤ λ/100 RMS	λ/200 RMS
Reflectance at 1216Å	≥ 78%	82%
Reflectance at 2537Å	≥ 86%	88%

* assumes temperature stability of ±0.07°C at 10" C and 1 mrad tilt
† assumes temperature stability of ±1°C at 10" C and 1 mrad tilt
‡ includes as-built performance of drive electronics

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